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Internal Kinematics of Distant Field Galaxies: I. Emission Linewidths for a Complete Sample of Faint Blue Galaxies at $\langle z \rangle \sim 0.25$

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ABSTRACT

We present measurements of the [OII] emission line width for a complete sample of 24 blue field galaxies ($21.25 < B < 22$, $B - R < 1.2$) at $\langle z \rangle \sim 0.25$, obtained with the AUTOFIB fibre spectrograph on the Anglo-Australian Telescope (AAT). Most emission lines are spectrally resolved, yet all have dispersions $\sigma_v < 100\,\mathrm{km\ s^{-1}}$. Five of the 24 sample members have [OII] doublet line flux ratios which imply gas densities in excess of 100 cm^{-3}. The line emission in these galaxies may be dominated by an active nucleus and the galaxies have been eliminated from the subsequent analysis. The remaining 19 linewidths are too large by a factor of two (7σ significance) to be attributed to turbulent motions within an individual star forming region, and therefore most likely reflect the orbital motion of ionized gas in the galaxy. We use Fabry–Perot observations of nearby galaxies to construct simulated datasets that mimic our observational setup at $z \sim 0.25$; these allow us to compute the expected distribution of (observable) linewidths σ_v for

a galaxy of a given "true" (optical) rotation speed v_c. These simulations include the effects of random viewing angles, clumpy line emission, finite fibre aperture, and internal dust extinction on the emission line profile. We assume a linewidth–luminosity–colour relation:

$$\log\Big[v_c\big(M_B,\ B{-}R\big)\Big] \;=\; \log[v_c(-19,\,1)] - \eta\,\big(M_B{+}19\big) + \zeta\,[(B{-}R){-}1]$$

and determine the range of parameters consistent with our data. We find a mean rotation speed of $v_c(-19,\,1) = 66 \pm 8\,\mathrm{km\ s^{-1}}$ (68% confidence limits) for the distant galaxies with $M_B = -19$ and $B - R = 1$, with a magnitude dependence for v_c of $\eta = 0.07 \pm 0.08$, and a colour dependence of $\zeta = 0.28 \pm 0.25$. Through comparison with several local samples we show that this value of $v_c(-19,\,1)$ is significantly lower than the optical rotation speed of present-day galaxies with the same absolute magnitude and rest frame colour ($\approx 105\,\mathrm{km\ s^{-1}}$). The most straightforward interpretation is that the distant blue, sub-L_* galaxies are about 1.5 mag brighter (and ≥ 0.8 mag brighter at 99% confidence) than local galaxies of the same linewidth and colour.

Key words: galaxies: evolution, kinematics, fundamental parameters – cosmology: observations

1 INTRODUCTION

In the last decade, large ground-based telescopes, HST and sensitive detectors have made it possible to study galaxy properties over cosmological distances in order to obtain direct constraints on galaxy evolution. One of the most surprising results of these studies has been the high number counts of "blue" field galaxies at magnitudes fainter than $B \sim 20$ (Kron 1980; Tyson 1988). Even though these counts suggest significant evolutionary effects, the shape of the measured redshift distribution of blue-selected galaxies ($B \leq 23$) is consistent with no-evolution models (Broadhurst *et al.* 1988; Colless *et al.* 1990, hereafter referred to as CETH; Lilly *et al.* 1991; Colless *et al.* 1993b). Further, deep imaging surveys in the red or near infrared bandpasses

yield galaxy counts which do not indicate strong evolutionary effects (Cowie *et al.* 1993; Gardner *et al.* 1993).

These puzzling observational results have prompted a large number of models to explain the observations. These models fall into two broad classes in their approach. First, there are *ad hoc* models, which assume some evolution of galaxy properties (number density, luminosity, etc.) and test which of these scenarios are consistent with the observations. The evolutionary effects in these models are *not* directly related to the physics of galaxy formation. The no-evolution hypothesis, mild and strong luminosity and spectral evolution models (Tinsley 1972; Guiderdoni & Rocca-Volmerange 1990; Gronwall & Koo 1995), the differential luminosity evolution model (Broadhurst *et al.* 1988), the rapidly fading/disappearing dwarf galaxy picture (Babul & Rees 1991), and number density evolution models (cf. the merging scenario of Broadhurst *et al.* 1992) fall into the first category. A second class of evolutionary models tries to incorporate a substantial amount of independent information about the hierarchical formation of structure in the Universe (cf. Kauffmann *et al.* 1994; Cole *et al.* 1994). There the number density of collapsed, virialized structures is derived as a function of epoch from a given cosmogonic scenario (e.g., a cold dark matter cosmogony), and combined with prescriptions for the merging and star-formation history of galaxies. The luminosity and density evolution of galaxies are coupled in this latter class of models.

Even though these models differ widely in many aspects, they share a common feature: the bulk of the evolutionary changes are attributed to intrinsically faint ($L < 0.5\ L^*$), blue galaxies. This feature can explain the paucity of galaxies with $z \gtrsim 1$ in redshift surveys of B-selected galaxies, and may explain why evolutionary effects appear to be stronger in observations at shorter wavelengths. The observed number counts and redshift distribution constrain the overall evolution of the galaxy luminosity function, but do not provide a unique prescription for the evolutionary history of *individual* galaxies. Therefore it is still a wide open question to which

extent the evolution of the luminosity function is caused by changes in the luminosity of individual galaxies or by changes in number density of visible galaxies.

The key to understanding the evolution of individual galaxies lies in the identification of the local counterparts of distant galaxies. In this paper we try to establish a link between distant and local galaxies by comparing the relation between the spatially integrated Doppler linewidth (LW) of the ionized gas to the continuum luminosity in the two populations. This observational test effectively seeks to determine how the luminosity of galaxies of a given LW or mass scale—i.e., the specific luminosity of galaxies—changes from moderate redshifts to the present day, and thereby addresses the question of "luminosity evolution" directly.

Various workers have shown that it is feasible to obtain line-width measurements and rotation curves for galaxies at cosmologically significant distances (Vogt *et al.*1993, Colless 1994, Koo *et al.* 1995; Rix, Colless and Guhathakurta, 1995; Guzman *et al.* 1996; Vogt *et al.* 1996). The are three important new elements in this paper: (1) a statistically well defined sample, (2) detailed modeling of the observations, and (3) a careful comparison with properly chosen local galaxy samples.

We have carried out an experiment to determine the global LW of the ionized gas—using the [OII] doublet—in a complete, magnitude-limited sample of blue field galaxies at $\langle z \rangle \sim 0.25$. Using a fibre spectrograph, we have performed the optical analog of a single beam HI LW measurement. The target galaxies have the magnitudes and colours of local, small, star-forming spiral galaxies (similar to the Large Magellanic Cloud), and we compare the measured LWs of these target galaxies with the LWs of probable local counterparts, after correcting for several biases inherent in such measurements.

The paper is organized as follows: Sec. 2 contains a description of the target sample, observations, and data reduction, and a discussion of how the LWs are measured from the data. In Sec. 3, we interpret the measured LW is terms of the characteristic rotation speed of the galaxy, and study the correlation of the galaxies' rotation speed with their absolute luminosity and colour. In Sec. 4, we compare the rotation speeds

of distant galaxies to those of local counterparts in order to quantify the evolution of field galaxies. The main points of this paper are summarized in Sec. 5.

A Hubble constant of $H_0 = 70\,\mathrm{km\ s^{-1}\,Mpc^{-1}}$ and flat space-time ($q_0 = 0.5$) are assumed throughout.

2 SAMPLE SELECTION, OBSERVATIONS, AND DATA REDUCTION

2.1 The Target Sample

The target galaxies were chosen at random from the photometric database used by CETH for the LDSS-1 survey, on the basis of the following criteria: (a) apparent blue magnitudes in the range $21.25 \leq b_J \leq 22$, and (b) colours bluer than $b_J - r_F \leq 1.2$. (For the sake of convenience, we use the symbols B and R in the rest of the paper when referring to magnitudes in the b_J and r_F bands, as defined in CETH.) In addition to the magnitude and colour criteria used to define the target sample, the final sample of LWs includes only galaxies with moderate to strong [O II] emission (equivalent widths $\gtrsim 10$ Å) within the observed redshift range $0.16 < z < 0.37$, which corresponds to the spectral window for [O II] in our setup. In Sec. 2.4, we demonstrate that for most galaxies that satisfy criteria (a) and (b) the requirement of detectable [O II] emission does not impose any additional restriction.

Our colour cut corresponds to the rest frame colours of Scd galaxies at a redshift of 0.25 (cf. Fig. 12 in CETH), and has been designed to yield a high fraction of galaxies with detectable emission lines. The photometric database from which the galaxies for CETH's LDSS-1 redshift survey were drawn (Jones *et al.* 1991) contains 764 galaxies in our chosen apparent magnitude range, $21.25 < B < 22$, and 463 ($= 61\% \pm 3\%$) of these are in our chosen colour range, $B - R < 1.2$. The colour distribution of nearly 2000 galaxies with $21 < B < 22$ in Kron's (1980) photometric sample indicates that $\gtrsim 50\%$ of the galaxies within this apparent magnitude range survive our colour cut. The median galaxy in our sample ($B = 21.7$ at $z = 0.25$) has an absolute blue

magnitude of $M_B \sim -19.0$, or $0.25\ L_B^*$ [$L_B^* = -20.6$ for $H_0 = 70\,\mathrm{km\ s^{-1}\,Mpc^{-1}}$ (Efstathiou *et al.* 1988)]. The absolute magnitudes of the galaxies listed in Table 1 were calculated from their apparent B magnitudes, accounting for their luminosity distance and a K-correction for Scd galaxies (cf. Fig. 13.7 in Peebles 1993).

2.2 Observations

The high-resolution spectra presented in this paper were obtained with the AUTOFIB multifibre spectrograph at the Anglo-Australian Telescope (AAT) on 1993 October 12, with seeing of $\approx 1''.7$. A 1200 lines mm^{-1} grating was used to cover the spectral region from 4300 Å to 5110 Å at a dispersion of 0.79 Å pixel^{-1}. The wavelength coverage was chosen to detect redshifted [OII] (3727 Å) emission line doublets in galaxies with $0.16 < z < 0.37$, a redshift range centred on the peak of the redshift distribution of $B = 21.25$–22 galaxies to maximize the [OII] detection rate. The instrumental resolution is $\sigma = 0.82$ Å (FWHM = 1.9 Å), which corresponds to $\sigma = 56\,\mathrm{km\ s^{-1}}$ and $48\,\mathrm{km\ s^{-1}}$ at the blue and red ends of the spectral range, respectively. The doublet nature of the [OII] emission line, with a doublet separation of $\Delta\lambda = 2.75$ Å, is resolved at the instrumental resolution. This makes it necessary to tailor the data reduction process (Sec. 2.5), but has the advantage of allowing an unambiguous redshift determination based on only one emission line.

The spectra were recorded on a 1024×1024 Tektronix CCD. The AUTOFIB spectrograph contains 60 usable fibres, each $2''.1$ in diameter, which can be positioned over a $40'$ diameter circular field. Engineering tests indicate that the fibres can be positioned with an accuracy of $0''.3$ rms. The overall throughput of the system is a little under 1%. Of the 60 fibres, 49 were positioned on target galaxies in the FBG1 field. The approximate coordinates of the field center are: $\alpha_{1950} = 00^{\rm h}54^{\rm m}51^{\rm s}$; $\delta_{1950} = -27°51'$.

Five of the remaining fibres were positioned at random 'blank' sky locations in order to measure (and to subsequently subtract) the night sky spectrum, while six were pointed at nearby bright stars that served as astrometric references. The total

exposure time on the FBG1 field was 7 hr, split into individual 1 hr exposures. The 1 hr target exposures were interspersed with short (2 min) calibration exposures of Cu–Ar and Fe–Ar arc lamps. The seeing was about $1\overset{''}{.}7$ (FWHM) as measured off the astrometric reference stars which were observed through fibre bundles. Bias frames and short flat field exposures of the twilight sky and of a tungsten lamp (white light source) were also obtained.

2.3 Data Reduction

The fibre spectra were reduced using standard procedures in the IRAF packages CCDPROC and DOHYDRA. The individual 1 hr CCD frames were flat fielded, the wavelength scale in the FBG1 spectra calibrated using arc lamp spectra, and the data combined after rejection of cosmic ray events. A one-dimensional, optimally weighted, mean spectrum was extracted for each fibre from the combined CCD data, using the flat field image to define the response profile of each fibre and the locus of its spectrum on the CCD array. The spectra are dominated by night sky continuum emission outside the [O II] lines, and the lines occupy a very small fraction ($< 1\%$) of the full spectral range; the continuum flux is undetectable for most galaxies. The median of all spectra (galaxy and blank sky) was used to define an accurate template of the night sky spectrum and it was subtracted from each galaxy's spectrum. The sky-subtracted spectra of all 24 galaxies in which [O II] emission is detected are shown in Figure 1.

2.4 Detection Limits for [OII] Emission

2.4.1 Detection Algorithm

We can devise an objective detection criterion for the emission lines, because galaxies with clearly detected [O II] will not have any other emission line in the observed spectral range; the portion of the spectrum outside the [O II] line therefore provides an empirical estimate of the effective noise in the data, including Poisson noise, sky subtraction error, residual cosmic rays, and flat fielding error.

We convolve the spectrum of each galaxy with a sequence of template [OII] line profiles, each centered on the k-th pixel (with $20 \leq k \leq 1004$, the portion of the CCD free from edge artifacts). The templates are double Gaussians of equal height and instrumental linewidth ($\sigma_{\rm instr} = 0.82\,$Å), broadened by various amounts to account for the intrinsic galaxy LW. The correlation amplitude $C(k)$, resulting from the convolution of these templates with the data, has a strong maximum $C_{\rm max}$ at the redshift of any obvious [OII] emission line. We calculate the rms variation, ΔC, of $C(k)$ from the rest of the spectrum and determine the ratio of the *second* highest maximum of $C(k)$ to ΔC. Since this second maximum must be due to noise, we can determine how high to set a threshold to avoid such spurious detections. Applying this statistic to all spectra with "clear" detections, i.e., with $C_{\rm max}/\Delta C \geq 10$, indicates that a threshold $C_{\rm thresh}/\Delta C = 4.5$ avoids any false detection. Using a narrow template of width, $\sigma = [\sigma^2_{\rm instr} + (40\,{\rm km\ s}^{-1})^2]^{1/2}$, we searched all 49 target galaxy spectra, detecting 24 galaxies with $C_{\rm max} > C_{\rm thresh}$ $(4.5\,\Delta C)$. A histogram of detection significances is given in Figure 3 and the observed properties of these galaxies are listed in Table 1*.

As narrow emission lines have a higher contrast against the galaxy's continuum and sky background than broad lines, they are easier to detect. To check how our detection limit depends on LW, we have repeated the above procedure, broadening the template by $0\,{\rm km\ s}^{-1} < \sigma_v \leq 300\,{\rm km\ s}^{-1}$. The convolution with broader templates resulted in no additional detections over those listed in Table 1. Further, all but one of the existing [OII] lines could have been detected even if their LWs had been as large as $\sigma_v \leq 200\,{\rm km\ s}^{-1}$(for a given total line flux). We conclude that our detection efficiency is approximately uniform for $\sigma_v \leq 200\,{\rm km\ s}^{-1}$. The fact that all of the 24 galaxies detected have LWs $\sigma_v < 100\,{\rm km\ s}^{-1}$ is *not* the result of a detection bias.

* Note that for convenience we use units of both Å and km s^{-1} for the dispersion σ; the ratio of these two quantities is λ/c for the instrumental dispersion, $\sigma_{\rm instr}$, and λ_0/c for the intrinsic rest frame dispersion of the [OII] lines, σ_v.

2.4.2 Completeness

There are two independent arguments that we have detected most, possibly all, of the target galaxies ($21.25 < B < 22,\ B-R < 1.2$) within the searched redshift range ($0.16 < z < 0.37$).

(1) The strength of the emission line in most detected objects, as measured by the value of C_{max}, is considerably higher than the detection threshold $C_{\mathrm{thresh}} = 4.5\Delta C$. The weakest detection is $5.4\,\Delta C$, and the median detection amplitude is $11\,\Delta C$, as shown in Figure 3. If most of the true [OII] line fluxes for this sample of blue galaxies were below our detection limit and if we just saw the tip of the iceberg, we would have expected to find the majority of detected galaxies very close to the limit $C_{\mathrm{max}} \approx C_{\mathrm{thresh}}$.

(2) Complete redshift surveys (CETH; Colless *et al.* 1993a) show that about 45%±10% of all field galaxies in the magnitude range of our target sample ($21.25 < B < 22$) have redshifts between 0.16 and 0.37. Our detection rate, 24 out of 49, is consistent with this. Given the Poisson error in the number of galaxies (20%) and large scale clustering of faint galaxies (e.g., the redshift "spikes" seen in the survey by Broadhurst *et al.* 1988), we conclude that we have detected *at least* 75% of the target galaxies within our surveyed redshift range, and possibly all of them.

Hence we believe that we are measuring LWs for a well-defined, representative sample of distant field galaxies.

2.5 Measuring the [OII] Linewidths

In measuring linewidths for the galaxies in our sample, we must account for several factors:

- We do not know the shape of the line profile *a priori*. This is because the shape of the rotation curve is unknown, because the emission from ionized gas is lumpy and often asymmetric with respect to the dynamical center of the host galaxy, and

because not all of it comes from the flat part of the rotation curve (cf. Schommer *et al.* 1993; also Sec. 3.1).

- The [OII] (3727Å) line is a doublet whose line flux ratio $R_{[\mathrm{OII}]}$ depends on the electron density in the line emitting gas. This ratio must be determined from the data.
- The rest frame separation of the [OII] doublet [$(\Delta\lambda)_0 = 2.75$ Å] is not much larger than the instrumental resolution and/or the typical kinematic line broadening observed in our galaxy sample.

We cope with these complications by choosing a specific model for the line profile of the doublet:

$$I_{\mathrm{mod}}(\lambda) = I_0 \left[\exp\left\{-\frac{[\lambda-\lambda_z]^2}{2[\sigma_z^2+\sigma_{\mathrm{instr}}^2]}\right\} + R_{[\mathrm{OII}]}\exp\left\{-\frac{[\lambda-\lambda_{z\epsilon}]^2}{2[\sigma_{z\epsilon}^2+\sigma_{\mathrm{instr}}^2]}\right\}\right], \tag{1}$$

with $\lambda_z \equiv (1+z)\lambda_0$, $\lambda_{z\epsilon} \equiv (1+z)(1+\epsilon)\lambda_0$, $\sigma_z \equiv (1+z)\sigma_v$, $\sigma_{z\epsilon} \equiv (1+z)(1+\epsilon)\sigma_v$, and $\lambda_0 = 3726.05$ Å. This form incorporates the known doublet separation expressed as a fractional difference, $\epsilon = (\Delta\lambda)_0/\lambda_0 = 7.3805 \times 10^{-4}$, and ensures identical rest frame velocity dispersions, σ_v (in λ units), for the two doublet components. It approximates the instrumental line profile by a Gaussian whose width, $\sigma_{\mathrm{instr}} = 0.82$ Å, has been determined from the widths of Cu–Ar and Fe–Ar arc lamp lines.

By choosing the functional form given in Eq. (1), we *define* the galaxy's LW as the σ of the best fitting Gaussian to the observed emission line profile. The parameters to be fit are the line amplitude I_0, the [OII] doublet flux ratio $R_{[\mathrm{OII}]}$, the redshift z, and the rest frame intrinsic dispersion of the emission line σ_v ($\sigma_v[\text{Å}] = \sigma_v[\mathrm{km\ s^{-1}}]\lambda_0/c$). Further, a linear continuum baseline is fitted simultaneously over the 80 pixels neighbouring the emission line.

The best fit parameters ($I_0,\ R_{[\mathrm{OII}]},\ z,\ \sigma_v$) are determined by minimizing χ^2,

$$\chi^2 = \sum_{\mathrm{pixel}\ k}\left(\frac{I_{\mathrm{mod}}(\lambda)-I_k}{\Delta I_k}\right)^2 \quad , \tag{2}$$

directly in pixel space (cf. Rix & White 1992). The quantities I_k and ΔI_k are the observed intensity and noise levels, respectively, at the k-th pixel with wavelength λ.

The "1σ" error bars on the best fit values of the individual parameters are determined by finding the region of parameter space for which $\chi^2 - \chi^2_{\rm min} = 1$. The upper and lower error bars are calculated separately. The two error estimates are comparable for most parameters and for most objects, except for low values of σ_v (see upper panel of Fig. 2) and we tabulate the geometric mean of the two error estimates, $\Delta_v^{\rm obs}$.

The best fit line parameters for all 24 galaxies are given in Table 1. The corresponding fits are superimposed onto the data in Figure 1; Figure 2 shows two of the fits in detail.

The line luminosities, $L_{\rm [OII]}$, and equivalent widths, EW, listed in Table 1 are not based on flux calibrations. Instead, they have been calculated from the exposure time, assuming an overall instrumental efficiency of 0.9%. Non-photometric conditions during the observations and inaccuracies in the fibre throughput calibration result in a factor of two uncertainty in the determination of $L_{\rm [OII]}$ and EW. Note that for positive definite quantities such as the dispersion, the "best fit" value is not an unbiased estimator of the true value when the error is comparable to the measured value (cf. Wardle & Kronenberg 1974). In this regime, the probability distribution can be approximated by a mean of $\sigma_v \equiv \sqrt{\sigma^2_{v,\,\rm fit} - (\Delta_v^{\rm obs})^2}$ and a dispersion of $\Delta_v^{\rm obs}$, where $\Delta_v^{\rm obs}$ is the geometric mean of the upper and lower errors derived from the χ^2 fit. The best fit values of the velocity dispersion, $\sigma_{v,\,\rm iit}$, are presented in Table 1 and in Figure 4; In the analysis of Sec. 3, however, we use the corrected values. Note that errorbars, $\Delta_v^{\rm obs}$, listed in Table 1, Figure 4 and Equation 5 are the geometric mean of the upper and lower errorbars.

The main observational results based on these fits are displayed in Figure 4, which shows several properties of the 24 galaxies with detectable [O II] emission as a function of their LW. This plot shows that the emission lines of most galaxies are resolved, but that all LWs are small: $\sigma_v < 100\,{\rm km\ s^{-1}}$. There are weak correlations between the observed LW (σ_v in Fig. 4) and other global galaxy properties. Firstly, the LWs appear to be somewhat larger for galaxies of greater [O II] emission line luminosity. Secondly, the median LW tends to increase with increasing continuum

(B band) luminosity. The statistical significance of the trends and a comparison with corresponding measurements in the local gal.axy population will be given in Sec. 3 and 4.

The [OII] doublet flux ratio, $R_{[\mathrm{OII}]}$, for most galaxies is found to be near the low density value of 1.45 (for $n_e \lesssim 10^{2.5}\,\mathrm{cm}^{-3}$; see Osterbrock 1989, p. 134), consistent with the line ratios found in HII regions. Five of the 24 galaxies in our sample have doublet line flux ratios, $R_{[\mathrm{OII}]} \ll 1.32$, indicating gas densities significantly ($\geq 2\sigma$) in excess of $100\,\mathrm{cm}^{-3}$. These objects are shown by the open symbols in Figure 4. The [OII] flux in these may arise predominantly from an active nucleus, as the LWs and inferred gas densities are comparable to those of LINERS (Ho, Filippenko and Sargent, 1993). In this small, but non-negligible fraction of our blue galaxy sample (5/24), the large emission line EW may not indicate vigorous star formation, but rather an AGN. This is in agreement with the spectroscopic results of Tresse *et al.* (1996) who find that the integrated emission line flux ratios for $\sim 20\%$ of blue field galaxies are inconsistent with standard HII region spectra, and are similar to the ratios found in LINERs. Since we are interested in what the [OII] linewidths might tell us about the global gas kinematics on kiloparsec scales, we exclude these five objects from the subsequent analysis.

3 ANALYSIS

In this section, we describe a set of steps that are essential for understanding what our LW measurements might be telling us about luminosity evolution in galaxies. First, we show that the line profiles must be broadened by global orbital motion (rotation) of the ionized gas in the galaxy; this is done by showing that the observed LWs are much larger than expected from the turbulent motions in individual star forming complexes. Second, we quantify the bias in the measurement of the rotation speed v_c from the LW measurement by using the observed properties of nearby small galaxies, the potential local counterparts of the distant galaxies in our sample. For a null-

hypothesis prediction we use Fabry–Perot (FP) datacubes of these nearby galaxies to simulate the expected distribution of measured LWs, σ_v at given v_c for these galaxies if they were observed at $z \sim 0.25$ with our AAT/AUTOFIB fibre setup. Third, we devise a maximum likelihood test to determine what range of linewidth–luminosity–colour relations are consistent with the data.

3.1 Do the Measured Linewidths Reflect Turbulent Gas Motions?

3.1.1 Relation between Linewidth and Emission Line Luminosity

Melnick *et al.* (1989) have shown that there is a well determined relation between the Hβ line luminosity, $L_{\mathrm{H}\beta}$, and the mean (Gaussian) LW, $\overline{\sigma_L}$, for giant H II regions and "H II galaxies". Presumably, these LWs arise from turbulent motions within the H II regions, powered by star formation activity and the resulting supernovae. Melnick *et al.* find that this relation takes the form:

$$\log(\overline{\sigma_L}) = \log(\overline{\sigma_{40.5}}) + \eta \log(L_{\mathrm{H}\beta}/L_{40.5}) \tag{3}$$

where $\overline{\sigma_{40.5}}$ is the mean LW at $L_{\mathrm{H}\beta} = L_{40.5} \equiv 10^{40.5}\,\mathrm{ergs\ s^{-1}\,cm^{-2}}$ and the slope of the relation is $\eta = 0.2$. This relation holds over the range $38.5 \leq \log(L_{\mathrm{H}\beta}) \leq 42$, with a remarkably low scatter of only $\Delta_L \sim 0.06$ in $\log(\sigma_L)$. The emission line broadening due to turbulent motion is expected to be very similar for different emission lines. To check whether our $L_{[\mathrm{OII}]}$–σ_v data for distant galaxies are consistent with the local $L_{\mathrm{H}\beta}$–σ_v relationship, we use the observed mean line flux ratio for field galaxies at $\langle z \rangle \sim 0.25$ (Tresse *et al.* 1996): $\langle L_{[\mathrm{OII}]}/L_{\mathrm{H}\beta} \rangle \sim 4.5$, with a scatter of a factor of two. Applying this mean line flux ratio and adjusting the Melnick *et al.* (1989) fit to $H_0 = 70\,\mathrm{km\ s^{-1}\,Mpc^{-1}}$, we expect $\log(\overline{\sigma_{40.5}}) = 1.28$ for the [O II] line—i.e., $\sigma_L \sim 19\,\mathrm{km\ s^{-1}}$ for a galaxy with an [O II] emission line luminosity of $L_{[\mathrm{OII}]} = 10^{40.5}\,\mathrm{ergs\ s^{-1}\,cm^{-2}}$.

3.1.2 Likelihood Analysis

We apply a maximum likelihood test to our galaxy sample in order to determine the best fit parameters $[\log(\overline{\sigma_{40.5}}),\, \eta,\, \Delta_L]$ and their associated errors. The relation given in Eq. (3), with an intrinsic scatter Δ_L in $\log(\sigma_L)$, predicts a LW distribution:

$$p_L^{\rm pred}(\sigma_v) = \frac{1}{\sqrt{2\pi}\Delta_L} \exp\left(-\frac{[\log(\sigma_v) - \log(\overline{\sigma}_L)]^2}{2(\Delta_L)^2}\right) \quad , \tag{4}$$

where $\overline{\sigma}_L$ is the mean velocity dispersion predicted for an "HII galaxy" with [OII] line luminosity, $L_{\rm [OII]}$. On the other hand, the probability distribution of the (true) LW, σ_v, given a measured value of $\sigma_v^{\rm obs}$ and its error, $\Delta_v^{\rm obs}$, is approximated by

$$p^{\rm obs}(\sigma_v) = \frac{1}{\sqrt{2\pi}\Delta_v^{\rm obs}} \exp\left(-\frac{(\sigma_v - \sigma_v^{\rm obs})^2}{2(\Delta_v^{\rm obs})^2}\right) \quad . \tag{5}$$

For any parameter set $[\log(\overline{\sigma}_{40.5}),\, \eta,\, \Delta_L]$, the probability of making the observation $[\log(L_{\rm [OII]}),\, \sigma_v^{\rm obs}]$, is given by

$$p[\log(L_{\rm [OII]}),\, \sigma_v^{\rm obs}] = \int_0^\infty p^{\rm obs}(\sigma)\; p_L^{\rm pred}(\sigma)\, d\sigma \quad . \tag{6}$$

The likelihood of a $L_{\rm [OII]}$–σ_v relation, given N observations, is then

$$\mathcal{L}\Big[\log(\overline{\sigma_{40.5}}),\, \eta,\, \Delta_L\Big] = \sum_{i=1}^{N} \log\Big[p(\log(L_{\rm [OII]}),\, \sigma_v^{\rm obs})\Big] \quad . \tag{7}$$

The best parameters are determined by maximizing the likelihood in Eq. (13) and their confidence intervals are derived from the distribution of $2(\mathcal{L}_{\rm max} - \mathcal{L})$ (cf. Wilks 1962), which is asymptotically distributed as a χ^2 distribution of n degrees of freedom and where n is the number of parameters considered simultaneously. The maximum likelihood analysis yields the following results: (a) a well determined zero point of the relation, $\log(\overline{\sigma_{40.5}}) = 1.62 \pm 0.05$ or $\overline{\sigma_{40.5}} = 42 \pm 3\,{\rm km\ s^{-1}}$, which is *larger by* 7σ than the value in the Melnick *et al.* (1989) relation $[\log(\overline{\sigma_{40.5}}) = 1.28$ or $\overline{\sigma_{40.5}} = 19\,{\rm km\ s^{-1}}]$; (b) a slope $\eta = 0.19 \pm 0.08$, (c) a scatter $\Delta_L = 0.1^{+0.06}_{-0.10}$, indicating that most of the observed scatter is attributable to measurement error. Figure 5 shows the data points, the best fit (bold solid line) and its uncertainties (dot dashed lines), and the Melnick *et al.* relation (dotted line).

A direct likelihood ratio test shows that our best fit relation is inconsistent with the relation found by Melnick *et al.* (1989) at the $\geq 99.99\%$ level. At an [OII] line luminosity of $L_{[\mathrm{OII}]} = 3 \times 10^{40}\,\mathrm{ergs\ s^{-1}\,cm^{-2}}$, the mean LW observed in our distant galaxy sample is a factor of two higher than that predicted by the σ_v–$L_{\mathrm{H}\beta}$ relation for local HII galaxies. Put differently, local HII galaxies, whose turbulent LWs are comparable to those observed for the distant galaxies should have 50 times higher line luminosities. This suggests that the observed [OII] LWs in our distant galaxy sample are not determined by the turbulent motions within star forming regions, but rather reflect the global rotational motion of a disk of ionized gas, as they do in samples of local spiral galaxies.

3.2 Relating the Measured Linewidth to the Galaxy Rotation Speed

We calculate what distribution of measured linewidths, $p(\sigma_v|v_c)$, we should expect for typical local galaxies of a given rotation velocity, v_c, if we observed them at $z = 0.25$ with AAT/AUTOFIB. Such a mapping must account for the lack of spatial information in fibre spectroscopy and the effects of:

- A finite fibre aperture ($D = 2\farcs1$) and fibre pointing errors of $\sim 0\farcs3$ (a conservative assumption as engineering tests indicate a $0\farcs2$ pointing error).
- The shape of the rotation curve [$v_c(R) \neq$ constant]
- Clumpy and asymmetric spatial distribution of the ionized gas emissivity
- The absence of information about the disk inclination, i
- Seeing (FWHM $\sim 1\farcs7$)
- Fitting a Gaussian model line profile even though the "true" [OII] line profiles of galaxies may have a variety of different shapes

3.2.1 Construction of Galaxy Kinematical Models

As a first step, we construct a complete, two-dimensional model for the gas kinematics of each of three well-resolved local galaxies, ESO 215-G39, ESO 437-G34, and ESO 323-G73. The model specifies the mean velocity at every radius R and the line

emissivity at every point $(R,\, \theta)$ in the disk plane. "Reduced" FP data for the three local galaxies were kindly provided by T. Williams and P. Palunas. The basic properties of these galaxies are listed in Table 2. The galaxies were chosen because they cover a range in absolute magnitude and rest-frame colour similar to the members of the distant sample. The reduced FP data for each galaxy consist of: (a) the Hα "flux image", $I(x,\, y)$, as a function of position in the plane of the sky, and (b) the velocity field, $v_{\rm proj}(x,\, y)$, at points of sufficient line flux [$I(x, y) \approx 0$ at many points in the image]. The velocity field data are too sparse to allow the usual tilted ring fit; we instead resort to a more restricted model, one in which the galaxy is assumed to be axisymmetric and coplanar, and to have a rotation curve which can be well approximated by the parametric form:

$$v_{\rm rot}(R) \equiv v_c (1+x)^{\beta} (1+x^{-\gamma})^{-1/\gamma} \quad , \tag{8}$$

where $x \equiv R/R_0$. Despite the awkward appearance of the above functional form, each parameter has a simple interpretation: v_c is the velocity scale, R_0 is the "turnover" radius (or core radius), γ determines the sharpness of the turnover (the higher the value of γ, the sharper the turnover), and the index β specifies the power-law behavior of the curve at large radii. This form of the rotation curve has a linear rise at small radii with a slope: $\partial v_{\rm rot}/\partial R \approx v_c/R_0$. In practice, the rotation curves are nearly flat at large radii ($|\beta| < 0.1$), and we set $\beta = 0$ in our model fits in order to have a well defined velocity scale.

In addition to the four rotation curve parameters, we fit the galaxy's center $(x_0,\, y_0)$, mean recession velocity, inclination, and major axis position angle. All nine parameters describing the velocity field are well constrained by the data for each of the three local galaxies, and these can be used to deproject the Hα image, $I(x,\, y) \rightarrow I(R,\, \theta)$. Some of these parameters are listed in Table 2. The best fit rotation curve and azimuthally averaged Hα flux distribution are shown in Figure 6. This figure also shows the size of a $2\farcs1$ fibre aperture if these local galaxies were observed

at $z = 0.25$ ($D = 7.6\,\mathrm{kpc}$). The aperture extends to twice the turnover radius R_0 for two of the galaxies, while $R_{\rm fibre} \approx R_0$ for the third.

3.2.2 Projection of Kinematical Models

The deprojected models of the three local galaxies, consisting of the ionized flux image, $I(R,\,\theta)$ and the rotation curve, $v_{\rm rot}(R)$, are projected to simulate the appearance of a $z = 0.25$ galaxy viewed from any arbitrary direction. To calculate the probability distribution, $p(\sigma_v|v_c)$, of measuring a width σ_v in a galaxy with a characteristic rotation speed v_c, we need to specify the distribution of disk inclination angles, $p[\cos(i)]$. A magnitude limited sample of dust free disk galaxies is expected to have a uniform distribution in $\cos(i)$.

For nearby spiral galaxies, however, it is well established that an inclination-dependent "internal extinction correction" must be made in calculating the true luminosity from the observed brightness, to account for dust within the disk of the galaxy. The magnitude of this correction is still under some debate (cf. Rix 1995), but the B band correction given in the Third Reference Catalog (de Vaucouleurs *et al.* 1991, hereafter RC3) is likely to be an upper limit: $A_B(i) = 1.5\min[\log_{10}(a/b),\,1]$, where the axis ratio b/a equals $\cos(i)$ for an infinitely thin circular disk. Galaxies at a given inclination i with "observed" (extincted) luminosities in the interval $[L,\,L{+}dL]$ have "true" (unextincted) luminosities in the interval $[e^{A_B(i)}L,\,e^{A_B(i)}(L+dL)]$. Since the value of $A_B(i)$ increases for more edge-on disks, a magnitude limited sample may be skewed towards face-on galaxies. For sub-L_B^* galaxies, however, this effect is small if the faint-end power law exponent of the luminosity function, α, is close to -1. If the luminosity function is a power-law with $\alpha = -1$ there are equally many galaxies in the interval $[L,\,L+dL]$ and $[\gamma L,\,\gamma(L+dL)]$. Specifically, if we adopt the faint-end slope for the local galaxy luminosity function $\alpha \approx -1.2$ (Efstathiou *et al.* 1988), the inclination distribution is only slightly skewed, with $\langle\cos(i) = 0.54\rangle$, compared to $\langle\cos(i) = 0.5\rangle$ for the dust-free case. Further, the average velocity reduction due to projection, $\langle\sin(i)\rangle$ differs by only 6% from the dust-free case.

The presence of dust also implies that a given apparent magnitude corresponds to a higher intrinsic luminosity than if the galaxy were free of dust. The average value of the internal extinction is $\langle A_B \rangle \approx 0.4$ for the skewed $\cos(i)$ distribution (compared to $\langle A_B \rangle = 0.6$ for a uniform distribution), and we adopt this value in the subsequent comparison of our distant galaxy sample to local samples (Sec. 4).

We simulate the AAT/AUTOFIB fibre observations by drawing an inclination from $p[\cos(i)]$ and a random major axis position angle φ_{maj} and by calculating the projected velocity, v_{proj}, at each point in the sky plane $(x,\, y)$ of the projected model of a local galaxy. To account for turbulent dispersion intrinsic to individual H II regions, the line profile at each point is assumed to be a Gaussian with a velocity dispersion of $15\,\mathrm{km\ s^{-1}}$.

Each pixel is given weight in proportion to its Hα emission line flux and the seeing is simulated by convolving each flux point (spatially) with a circular Gaussian of FWHM = $1''.7$. The emissivity weighted line profile is then obtained by integrating over the area of the (projected) galaxy model corresponding to the $2''.1$ (diameter) aperture of the AUTOFIB fibres. This aperture corresponds to a radius of 3.8 kpc at a redshift of 0.25. The effect of pointing error is simulated by shifting the center of the aperture (over which the integration is carried out) in a random direction, with the size of the shift drawn from a Gaussian distribution with rms dispersion $0''.3$. The integrated line profile for a given pair of viewing angles $(i,\, \varphi_{\mathrm{maj}})$ is fitted to a Gaussian in a least-squares sense; this is a non-trivial step if the true profile shapes are not Gaussian. Summing the projected galaxy model (of given v_c) over all orientation angles $(i,\, \varphi_{\mathrm{maj}})$ produces the probability, $p_{\mathrm{MC}}(\sigma_v|v_c)$, of measuring a dispersion σ_v with our fibre setup.

The probability distribution $p_{\mathrm{MC}}(\sigma_v|v_c)$ differs for the three galaxies because of differences in the shape of the rotation curve, in the spatial distribution of the emission line flux from ionized gas, and, most importantly, in the rotation velocity scale v_c. Also, we need to predict $p_{\mathrm{MC}}(\sigma_v|v_c)$ for *any* v_c in a certain range, even though we only have a small number of calibrating galaxies. We do this by assuming that the *shape*

of $p_{\rm MC}$ is constant and that the distribution scales with v_c. Mathematically speaking, we assume that $p_{\rm MC}(\sigma_v|v_c) = p(\sigma_v/v_c)$. The probability distributions for the three local galaxies are combined and the resulting mean $p(\sigma/v_c)$ is shown in Figure 7 along with the rms spread between the three curves. Note that this wide range of observed LWs, σ_v, at a given v_c, would arise even for infinite signal-to-noise observations with our technique.

The shape of $p(\sigma/v_c)$ deserves some comment, as it has a broad distribution with a mean value of $\sigma_v/v_c \sim 0.6$. These features arise from a combination of factors. For an edge-on galaxy with a uniform flux distribution in the plane of the disk, a perfectly centered aperture that is large enough to include the flat part of the rotation curve yields an integrated emission line profile is roughly rectangular; the Gaussian that best fits a rectangle extending between $-v_c$ and $+v_c$ has a width $\sigma_v \sim 0.75\,v_c$. This explains why $p(\sigma_v/v_c)$ falls off for $\sigma_v/v_c \gtrsim 0.8$. Any asymmetry in the shape of the integrated line profile, due to either a non-uniform flux distribution or fibre centering error, reduces further the fitted value of σ_v. The finite fibre size and central concentration of the ionized flux distribution tend to weight the rising part of the rotation curve at small radii at the expense of flat part at larger radii, and this too reduces the measured σ_v relative to v_c. The effect of seeing tends to *increase* the value of σ_v/v_c since it causes flux from the outer parts of the galaxy (at extreme velocities) to spill into the fibre aperture and flux from the central part of the galaxy to spill out of it. The tail at the low end of the distribution ($\sigma_v/v_c \lesssim 0.4$) arises from face-on galaxies. For a randomly oriented galaxy sample, the mean reduction in velocity due to projection effects (compared to an edge-on sample) is $\langle \sin(i) \rangle \sim 0.85$. All the above factors—the definition of σ_v, line profile asymmetries (caused by spatial inhomogeneities in the ionized flux and by fibre centering errors), central weighting of the galaxy (due to finite fibre size and centrally peaked ionized flux distribution), smearing due to seeing, and inclination effects—are of comparable importance, and all of them except seeing will reduce σ_v/v_c.

While we measure [O II] for the distant galaxies, the $p(\sigma_v/v_c)$ was derived from the

Hα distribution in local galaxies. It is interesting to ask how the spatial distributions of [OII] and Hα compare in local galaxies, since that determines the applicability of the derived $p(\sigma_v/v_c)$ to the distant galaxy sample. In a study of the star forming regions in 14 nearby spiral galaxies, Zaritsky *et al.* (1994) find that the [OII] flux is *less* centrally concentrated than the Hα flux. This is caused by a radial gradient in the intrinsic Hα/[OII] fluxes of HII regions (which, in turn, is related to their radial metallicity gradient) and in the amount of (selective) dust extinction (both increase with increasing radius). Both these effects cause our estimate of σ_v/v_c to be smaller than the "true" value, making our best fit value of the rotation speed, v_c (see Sec. 3.3.2) somewhat of an overestimate. This would imply that the discrepancy between the mean rotation speed of our distant galaxy sample and that of local galaxies is larger than we indicate in Sec. 4.

3.3 The Linewidth–Luminosity–Colour Relation

3.3.1 Fitting Procedure

We are now in a position to test whether our observations are consistent with any linewidth–luminosity (LWL) relation, or more generally, with any linewidth–luminosity–colour (LWLC) relation of the form:

$$\log\Big[v_c(M_B,\ B-R)\Big] \;=\; \log\left[v_c(-19,\,1)\right] \,-\, \eta\,(M_B+19) \,+\, \zeta\left[(B-R)-1\right]\ , \tag{9}$$

where $v_c(-19,\,1)$ is the mean circular velocity of a galaxy with absolute blue magnitude $M_B=-19$ and colour $B-R=1$, corresponding to our sample median. The dependence of the mean circular velocity on galaxy luminosity and colour are specified by the slopes, η and ζ, respectively.

If the LWLC relation has an intrinsic (logarithmic) scatter of Δ_v in velocity, then the probability of finding v_c, for a given luminosity and colour, is

$$p[v_c|M_B,\,B-R]\,\frac{dv_c}{v_c} \;=\; \frac{1}{\sqrt{2\pi}\Delta_v}\,\exp\left(-\frac{\Big(\log[v_c]-\log[v_c(M_B,\,B-R)]\Big)^2}{2\Delta_v^2}\right)\frac{dv_c}{v_c}\ . \tag{10}$$

As long as $\Delta_v \ll 1$, it matters little whether the scatter is specified in the velocity or in its logarithm. The predicted probability of measuring a LW σ_v for a galaxy of absolute magnitude M_B and colour $B-R$ is then

$$p^{\rm pred}(\sigma_v|M_B,\, B-R) \;=\; \int_0^\infty p_{\rm MC}(\sigma_v|v_c)\; p[v_c|M_B,\, B-R]\,\frac{dv_c}{v_c} \quad , \tag{11}$$

where the averaging and bias introduced by our observing technique (see Sec. 3.2) are incorporated through $p_{\rm MC}(\sigma_v|v_c)$. As in Sec. 3.1.2, this distribution must then be convolved with the measurement uncertainties in order to yield the probability of each galaxy observation, $\sigma_v^{\rm obs}$, given an assumed LWLC:

$$p(\sigma_v^{\rm obs}|M_B,\, B-R) \;=\; \int_0^\infty p^{\rm obs}(\sigma_v)\; p^{\rm pred}(\sigma_v|M_B,\, B-R)\; d\sigma \quad , \tag{12}$$

where $p^{\rm obs}(\sigma_v)$ is defined in Eq. (5). The likelihood, $\mathcal{L}$, of such a LWLC given all N observations is then

$$\mathcal{L}[v_c(-19,\,1),\,\eta,\,\zeta,\,\Delta_v] \;=\; \sum_{i=1}^{N}\,\log[p(\sigma_v^{\rm obs}|M_B,\, B-R)] \quad . \tag{13}$$

3.3.2 Likelihood Limits

The most likely values for the above parameters are determined by maximizing the likelihood in Eq. (13); their confidence intervals are derived from the distribution of $2(\mathcal{L}_{\rm max}-\mathcal{L})$ (cf. Wilks 1962). Figure 8 summarizes the result by showing two projections of the likelihood contours, that include the best fit value, in the $[v_c(-19,\,1),\,\eta]$ and $[v_c(-19,\,1),\,\zeta]$ planes, illustrating the dependence of v_c on M_B and $(B-R)$, respectively. The analysis yields best fit values of: $v_c(-19,\,1) \;=\; 66 \pm 8\,{\rm km\ s^{-1}}$, $\eta \;=\; 0.07 \pm 0.08$, and $\zeta \;=\; 0.28 \pm 0.25$. The projections of the best fit onto the $\mathrm{M}_B-\eta$ and $\mathrm{M}_B-\zeta$ plane are compared to the data in Figure 8. The likelihood limits of the parameters in the $\mathrm{M}_B-\eta$ and $\mathrm{M}_B-\zeta$ planes are shown in Figure 9.

The "zero point" of the LWLC relation is well determined. Note that the internal dust extinction is included in these models and enters in two ways: (1) it leads to a 0.4 mag correction for the mean B-band internal extinction for inclined spirals (Sec. 3.2.2), and (2) it results in a slight skewing of the inclination distribution towards

face-on galaxies, changing the inferred linewidth by $\sim$6%; these two effects "cancel" each other partially. There is some covariance between the zero point and the slope, $\eta \equiv -\partial \log(v_c)/\partial M_B$, because the median absolute magnitude of the distant galaxy sample is somewhat brighter than our reference value, $M_B = -19$.

As the top panel of Figure 9 shows, a wide range of slopes, $\eta \equiv -\partial \log(v_c)/\partial M_B$, is consistent with the data, including $\eta = 0$, the case of no luminosity dependence of v_c. This is caused in part by the limited absolute magnitude range of our sample of galaxies ($\Delta M_B \sim 2$ mag) and in part by the breadth of the $p(\sigma_v/v_c)$ distribution. Note that the typical LW–luminosity slope observed for local samples, $\eta \sim 0.12$ (Bothun *et al.* 1985; Fukugita *et al.* 1991), is also consistent with our data.

The bottom panel of Figure 9 shows the colour dependence of v_c through the likelihood contours in the $[v_c(-19, 1), \zeta]$ plane, at fixed η. The dependence of v_c on $B - R$, suggested by the bottom panel of Figure 4, is not significant: $\zeta \equiv \partial \log(v_c)/\partial(B - R) = 0.28 \pm 0.25$ (68% confidence limits).

In order to test the sensitivity of these results to the exact shape of the probability distribution, $p(\sigma_v/v_c)$, we have repeated the above likelihood analysis with the $p(\sigma_v/v_c)$ distributions derived separately for each of the three local calibrator galaxies. The three probability distributions are roughly similar in shape as shown by the error bars in Figure 7. The resulting 68% likelihood regions for any given parameter overlap substantially for these three realizations, indicating that the results for the three are consistent with one another.

The intrinsic scatter in the LWLC relation of distant galaxies [defined in Eq. (10)] is only weakly constrained: $\Delta_v < 0.32$ (90% upper limit). This may be understood as follows. The probability distribution, $p(\sigma_v/v_c)$, for any given v_c is very broad even if $\Delta_v = 0$. In the presence of finite intrinsic scatter in the LWLC relation, the resulting distribution of σ_v is a convolution of the intrinsic v_c spread (Gaussian with dispersion Δ_v) with $p(\sigma_v/v_c)$. The results are largely independent of the intrinsic scatter Δ_v, as long as it is at least a factor of two smaller than the spread in observed LWs, $p(\sigma_v/v_c)$, introduced by our LW measuring technique. This implies that the results

(including the size of the confidence regions) are insensitive to the value of Δ_v; we fix this parameter at its best fit value, $\Delta_v = 0.15$, in the rest of the analysis. Note, the intrinsic scatter is also consistent with zero.

4 COMPARING THE LINEWIDTH–LUMINOSITY RELATION FOR DISTANT VERSUS LOCAL GALAXIES

We now turn to a quantitative comparison of the LWLC in our distant sample to the properties of present day galaxies. This requires LW measurements in a set of local galaxies whose B luminosities and colours are similar to those of the distant field galaxies in our sample. Unfortunately, most galaxy samples targeted in Tully–Fisher studies are designed for optimal distance estimates, but do not provide an unbiased estimate of the LWLC relation for a statistically well defined population.

4.1 Relating the HI Linewidth $\mathbf{W_{20}}$ to the Optical Linewidth v_c

A large number of local galaxy LW measurements are based on HI single-dish data, usually defined to be the width of the HI line profile at 20% of the peak intensity, W_{20} (or equivalent measures such as W_{50}). To relate W_{20} to the optically measured "circular velocity" v_c, it is customary to set:

$$v_c \;=\; 0.5\, f\, W_{20}/\sin(i) \quad . \tag{14}$$

There are two main reasons why the correction factor f differs from unity. First, turbulent motions broaden the HI profile. Second, rotation curves are not perfectly flat at large radii, and the Hα-emitting ionized gas and neutral HI gas (used to measure v_c and W_{20}, respectively) may sample different radii. The relative importance of these two effects is still under debate and we resort to published Hα and HI studies to obtain an empirical calibration of the v_c - W_{20} relation. One of the largest samples of optical rotation curves is available from the survey by Mathewson *et al.* (1992a). In their analysis Mathewson *et al.* (1992b) they find that $v_c(\mathrm{H}\alpha) \sim 0.94\ (0.5\,W_{50}/\sin(i))$ for galaxies with $M_B \sim -19$; Rubin *et al.*(1985) and Courteau (1992) find that on

average $\langle v_c \rangle = v(W_{50})$ within a few percent, albeit for more luminous galaxies. If these results are combined with $W_{50} \approx 0.9\,W_{20}$ (*e.g.*Bothun *et al.*1985) this implies a correction factor of $f = 0.86 \pm 0.03$. Schommer *et al.* (1993) applied the turbulence correction advocated by Tully & Fouqué (1985) to a sample of galaxies for which they had both optical (Hα) and HI measurements (corresponding to $f = 0.83$), but found that a smaller correction ($f = 0.9$) was needed to bring the two measurements into agreement. In summary, these studies indicate that a correction of $f = 0.86 \pm 0.04$ should be applied for galaxies with $M_B \sim -19$ to go form $W_{20}/\sin(i)$ to $2v_c$.

In the subsequent comparison with local data, we adopt a correction factor of $f = 0.86$, which corresponds to correcting W_{20} downward by 14%.

4.2 Existing Tully–Fisher Studies

We consider two B band Tully–Fisher samples of nearby disk galaxies—those of Bothun *et al.* (1985) and Fukugita *et al.* (1991)—for comparison to our distant galaxy sample. The member galaxies of both of these samples are distant enough to yield sufficiently good relative distances relative to our $\langle z \rangle \sim 0.25$ sample, once scaled to the same Hubble constant. Further, both these Tully–Fisher samples contain a sizeable number of galaxies with luminosities as low as $M_B \sim -18$, and thus overlap in luminosity (and colour) with our sample of distant galaxies.

The B band study of Coma cluster galaxies by Fukugita *et al.* (1991) yields a mean rotation velocity, $v_c(-19) = 102\,\mathrm{km\ s^{-1}}$, for galaxies with $M_B = -19$. Bothun *et al.* (1985) list $B-V$ colours for their galaxies, allowing us to mimic the $b_J - r_F < 1.2$ color cut for the distant field galaxy sample. The resulting mean colour of this subsample is $B-V = 0.36$, comparable, after K-corrections and color transformations (Fukugita *et al.* 1995) to the mean (observed) colour of our $\langle z \rangle \sim 0.25$ galaxy sample. The zero point of the LWL relation for the colour-restricted Bothun *et al.* galaxy subset is not significantly different from that of the whole sample, $v_c(-19,\,1) = 102\,\mathrm{km\ s^{-1}}$, and is identical to Fukugita *et al.*'s 1991 value.

As the the LWs in these local Tully–Fisher samples were derived from HI measure-

ments, W_{20}, the quoted value for the "optical" rotation speeds, $v_c(-19) = 102\,\mathrm{km\ s^{-1}}$, include the 14% downward correction from Section 4.1. The parameters of the best fit LWL relations for these two local Tully–Fisher samples are shown in Figure 9, with a correction for $\mathrm{W}_{20} \rightarrow v_c$.

4.3 Local Linewidth–Luminosity–Colour Relation from RC3

Most nearby Tully–Fisher samples, including Fukugita *et al.* (1991) and Bothun *et al.* (1985), are restricted to a narrow range of Hubble types and usually exclude irregular galaxies. Our $\langle z \rangle \sim 0.25$ sample, however, has no morphological restriction. Since the mean v_c at a given M_B may vary with Hubble type (Rubin *et al.*1985), the local Tully–Fisher galaxies may not be directly comparable to the distant ones.

As a remedy, we have selected from the RC3 catalog a set of local galaxies with measured W_{20}, ignoring their Hubble type, requiring only:

a. Axis ratios $b/a < 0.7$, so that the uncertainty in the LW $\sin^{-1}(i)$ deprojection factor is small

b. Recession velocities $cz > 1000\,\mathrm{km\ s^{-1}}$ and angular separations of $> 10°$ from the center of the Virgo cluster, so that our distance estimate, $D = cz/H_0$, is not severely affected by peculiar velocities

The resulting RC3 sample includes galaxies as faint as $M_B = -17$ and many galaxies with $-18 > M_B > -20$, the absolute magnitude range spanned by our $\langle z \rangle \sim 0.25$ sample.

We construct a LWL relation for the blue ($B - V < 0.5$, $\langle B - V \rangle = 0.41$) and red ($B - V > 0.5$, $\langle B - V \rangle = 0.66$) subsample separately. This colour cut corresponds to the colour threshold, $b_J - r_F < 1.2$ used to select the distant galaxy sample. Both blue and red RC3 samples show a clear LWL trend, despite a scatter of almost a factor of 2 in v_c at fixed M_B. This scatter appears to be dominated by disk inclination errors. The zero point of the best fit LWL relation for the blue RC3 sample, $v_c(-19, \mathrm{blue}) = 110\,\mathrm{km\ s^{-1}}$, is in reasonable agreement with the zero points

of the morphologically-restricted Fukugita *et al.* (1991) and Bothun *et al.* (1985) samples. As discussed above, these zero point estimates include a 14% downward correction from $0.5\,W_{20}/\sin(i) \rightarrow v_c$. The best fit slope of the RC3 blue galaxy LWL relation, $\eta = 0.11$, is also consistent with that of the Fukugita *et al.* and Bothun *et al.* samples and with that of the distant galaxy sample.

The mean rotation velocity of $M_B = -19$ galaxies in the red RC3 sample, $v_c(-19, \mathrm{red}) = 129\,\mathrm{km\ s^{-1}}$, is significantly higher than in the blue sample, although the LWL slopes of the two samples are identical. This trend in the local v_c versus colour relation corresponds to a slope, $\zeta = +0.11$ (after converting the rest-frame $B-V$ colour for local galaxies to a redshifted $b_J - r_F$ colour at $z = 0.25$).

The colour dependence of v_c in local galaxies has an interesting implication. If the difference between the mean rotation speeds, $v_c(-19,\,1)$, of distant and local galaxies is caused by galaxies being brighter in the past, one also expects them to be somewhat bluer in the past (due to a younger mix of stars). In other words, the appropriate local counterpart of a $z = 0.25$ galaxy with $M_B = -19$ and $B-R = 1$, is not only one that is fainter but also one that is redder ($B-R > 1$). Since the mean v_c increases for redder galaxies locally, the offset in v_c between distant and local galaxies (and the amount of luminosity evolution it implies) would be even larger than we calculated in Sec. 4.2 had we taken colour evolution into account.

In summary, comparison of our linewidth data on blue field galaxies at $\langle z \rangle \sim 0.25$ with nearby galaxy data leads us to conclude that, at the $> 99\%$ confidence level, the distant galaxy sample does not have rotation speeds as high as that of local samples with similar photometric properties (B luminosity, $B-R$ colour). Taken at face value, the best fit rotation speed of blue $M_B = -19$ galaxies, $v_c(-19,\,1)$, is 35% smaller (at least 25% smaller at 90% confidence) than the local value. It is likely that this difference can be attributed to an epoch of increased star-formation, which lead to a larger luminosity at a given LW. Assuming the local B-band slope for the

LWL relation ($\eta \approx 0.12$), the off-set in $v_c(-19, 1)$ correponds to a magnitude offset of $\Delta M_B = 1.5$ mag, with a lower limit of 0.8 mag (99%).

5 CONCLUSIONS AND FUTURE WORK

We have presented results from an exploratory project to determine the relation between the kinematic and photometric properties of galaxies at cosmologically significant distances and to compare it to the relation found for local samples. The target of our study is a statistical sample of blue, sub-L_* field galaxies in the redshift range $0.16 < z < 0.37$, for which we have obtained high dispersion spectra to determine their [OII] emission LWs, integrated over an aperture of ~ 7.6 kpc diameter. The [OII] LWs are resolved ($\sigma \gtrsim 30\,\mathrm{km\ s^{-1}}$), yet the measured dispersions σ_v are < 100 km s^{-1} for all sample galaxies. For several reasons we believe that we have detected the [OII] emission and have measured LWs for most galaxies within the magnitude, color and redshift range; the sample is nearly complete. With the imposed colour cuts the sample constitutes the blue half of the galaxy population in this luminosity and redshift range.

The primary goal of our project is to test the null hypothesis that these distant galaxies have the same characteristic circular velocities, v_c, as local galaxies of the same absolute B magnitude and colour. We have used Hα Fabry–Perot data on local galaxies to mimic our fibre observations, and to thereby calibrate the biases/errors associated with the measurement of v_c from emission LWs. The following main conclusions arise from this analysis:

1. At a given emission line luminosity, the observed [OII] linewidths of distant galaxies are too large to be compatible with the relation between line luminosity and (turbulent) LW observed for nearby giant HII regions and HII galaxies. Further, 80% of the our sample members have [OII] doublet flux ratios that indicate gas densities of $\lesssim 100\,\mathrm{cm}^{-3}$, consistent with HII region spectra. Hence, the LWs of most objects reflect the orbital motion of ionized gas in the galaxy's potential

well. In the remaining 20% of objects, the emission line flux may arise from an active nucleus.

2. We have tested whether distant blue galaxies within a narrow range of absolute blue luminosity have the same mean v_c as local galaxies of the same absolute magnitude and colour. In order to make a realistic comparison, we have simulated what emission LWs would be measured at $z \sim 0.25$ for local galaxies of a given v_c, assuming that the shape of the rotation curve and spatial distribution of ionized gas are comparable in distant and local galaxies. We find that, at a given luminosity, $M_B \sim -19$, the distant galaxies have rotation speeds that are about 35% smaller than expected from photometrically identical, local samples. The LWs of the two samples are inconsistent at the $> 99.9\%$ confidence level.

3. The most likely explanation for the LW offset is that galaxies have undergone considerable luminosity evolution. Assuming the local B-band slope for the LWL relation ($\eta \approx 0.12$), the off-set in $v_c(-19, 1)$ correponds to a magnitude offset of $\Delta M_B = 1.5$ mag, with a lower limit of 0.8 mag (99%). If spectral evolution accompanies this luminosity evolution, the magnitude offset may be even larger. However, at this point it cannot yet be ruled out that the LW differences in the samples arise, at least in part, from a very different $v_c \rightarrow$[OII] mapping. Such differences could arise from either the shape of their rotation curve, and/or the spatial distribution of the line emitting gas.

This systematic investigation of low-luminosity, blue field galaxies, complements corresponding studies of massive, red cluster galaxies. Franx (1993) and van Dokkum and Franx (1996) studied the fundamental plane of early type galaxies in two clusters at $z = 0.19$ and $z = 0.4$. They found that galaxies of a given mass scale were brighter in the past by an amount that is consistent with a formation at high z and subsequent "passive evolution". Also, Lilly *et al.*(1996) find that the luminosity function evolves most strongly for low-luminosity blue galaxies. The present data indicate that this evolution of the luminosity *function* can be traced to the mass-to-light ratio evolution

of individual galaxies. However, we infer values of v_c for galaxies of $M_B = -19$ which are not as low as predicted for some dwarf starburst scenarios (*e.g.*Babul and Rees, 1992; Babul and Ferguson, 1996).

The present study represents only one step towards understanding the internal kinematics of distant field galaxies. Follow-up should address the following questions:

a. Is there evern more direct evidence that emission LWs reflect ordered rotation of ionized gas within these galaxies? We are currently pursuing this question with the help of Fabry–Perot imaging datacubes for a small sample of distant field galaxies (Ing *et al.* 1996; see also Vogt *et al.* 1993, 1996).

b. What is the spatial distribution of the emission line flux in these distant galaxies? Is it the same as for local galaxies, or are the observed small LWs in part due to a much more centrally concentrated flux distribution? A direct answer to these questions would require high angular resolution, narrow band images tuned to the redshifted [OII] line.

c. Can the scatter in the linewidth–luminosity relation be reduced if we correct for galaxy inclinations? A reduction in scatter is expected if, as we argue, the LW is dominated by gas motions in a disk. Inclinations of sufficient accuracy can be obtained from *HST* images.

d. What is the slope of the linewidth–luminosity relation for distant galaxies when we include a wider range of absolute magnitudes? We are analyzing high dispersion spectroscopic data obtained with the AAT/AUTOFIB instrument of nearly 100 galaxies spanning a broader range of M_B and colour than the sample presented here.

e. Is there a similar offset in the LWL relation when the luminosity is measured in a different bandpass? The amount of luminosity evolution is expected to be smaller in the rest-frame I band than in B. Near infrared (H-band) photometry is being carried out to test this hypothesis.

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REFERENCES

Babul, A., & Rees, M. J. 1992, MNRAS, 255, 346

Babul, A., & Ferguson, H., 1996, ApJ, 458, 100

Bothun, G. D., Aaronson, M., Schommer, B., Mould, J., Huchra, J. and Sullivan, W., 1985, ApJS, 57, 423

Broadhurst, T. J., Ellis, R. S., & Shanks, T. 1988, MNRAS, 235, 827

Broadhurst, T. J., Ellis, R. S., & Glazebrook, K. 1992, Nature, 355, 55

Cole, S., Aragon-Salamanca, A., Frenk, C., Navarro, J., & Zepf, S. 1994, MNRAS, 271, 781

Colless, M. M., Ellis, R. S., Taylor, K., & Hook, R. 1990, MNRAS, 244, 408 (CETH)

Colless, M. M., Ellis, R. S., Broadhurst, T. J., Taylor, K., Peterson, B. A. 1993a, MNRAS, 261, 19

Colless, M. M., Schade, D., Broadhurst, T. J., & Ellis, R. S. 1993b, MNRAS, 267, 1108

Courteau, S., 1992, *Ph.D. Thesis*, UC Santa Cruz

Cowie, L. L., Gardner, J.P., Hu, E. M., Songaila, A., Hodapp, K. W. and Wainscoat, R. J., 1994, ApJ, 434, 114.

Efstathiou, G., Ellis, R. S., & Peterson, B. A. 1988, MNRAS, 232, 431

Franx, M., 1993, PASP, 105, 1058

van Dokkum, P. and Franx, M., 1996, MNRAS, *in press*

Fukugita, M., Okamura, S., Tarusawa, S., Williams, B. and Rood, H. 1991, ApJ, 376, 8

Fukugita, M., Shimasaku, K. and Ichikawa, T., 1995, PASP, 107, 945.

Gardner, J.P., Cowie, L. L., & Wainscoat, R. J. 1993, ApJ, 415, L9

Gronwall, C., & Koo, D. C. 1995, ApJ, 440, L1

Guzman, R. *et al.*, 1995, ApJ, 460, L5

Ho, L., Filippenko, A. and Sargent, W., 1993, ApJ, 417, 63

Ing, K., Guhathakurta, P., Rix, H.-W., Williams, T. B., & Colless, M. M. 1996, ApJ, in preparation

Guiderdoni, B., & Rocca-Volmerange, B. 1990, A&A, 227, 362

Jones *et al.* 1991, MNRAS, 249, 481

Kaufmann, G., Guiderdoni, B., & White, S. D. M. 1994, MNRAS, 267, 981

Koo, D. C., & Kron, R. G. 1992, ARAA, 30, 613

Koo, D. C., *et al.*, 1995, ApJ, 440, L49

Kron, R. G. 1980, ApJS, 43, 305

Lilly, S. J., Cowie, L. L., & Gardner, J. P. 1991, ApJ, 369, 79

Lilly, S. J. *et al.*1995, ApJ, 455, 108

Mathewson, D., Ford, V., & Buchhorn, M. 1992a, ApJS, 81

Mathewson, D., Ford, V., & Buchhorn, M. 1992b, ApJL, 5

Melnick, J., Terlevich, R., & Moles, M. 1989, MNRAS, 235, 297

Osterbrock, D., 1989 *Astrophysics of Gaseous Nebulae*, University Science Books, Mill Valley

Peebles, P. J. E. 1993, *Principles of Physical Cosmology* (Princeton University Press, Princeton)

Rix, H.-W. & White, S. D. M. 1992, MNRAS, 254, 389

Rix, H.-W. 1995, in *The Opacity of Spiral Disks*, Ed. J. Davies and D. Burstein, Kluwer, Dortrecht.

Rix, H.-W., M. Colless and P. Guhathakurta, 1995, in *New Light on Galaxy Evolution*, IAU Symp. 171, Ed. R. Bender and R. Davies, Kluwer

Rubin, V., Burstein, D., Ford, W. and Thonnard, N., 1985, ApJ, 289, 89

Schommer, R. A., Bothun, G. D., Williams, T. B., & Mould, J. R. 1993, AJ, 105, 97

Thonnard, N. 1983, in *Besancson Symp. on Internal Kinematics of Galaxies* (Reidel)

Tinsley, B. M. 1972, ApJ, 178, 319

Tresse, L. *et al.*, 1996, astro-ph/9604028

Tully, R. B., & Fouqué, P. 1985, ApJS, 58, 67

Tyson, J. A. 1988, AJ, 96, 1

de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Jr., Buta, R. J., Paturel, G., & Fouqué, P. 1991, *Third Reference Catalogue of Bright Galaxies* (Springer, New York) (RC3)

Vogt, N. P., Herter, T., Haynes, M and Courteau, S. 1993, ApJ, 415, L95

Wardle, J. F. C., & Kronenberg, P. P. 1974, Ap.J., 194, 249

Wilks, S. S. 1962, *Mathematical Statistics* (Wiley & Sons, New York)

Zaritsky, D., Kennicutt, R. C., Jr., & Huchra, J. P. 1994, ApJ, 420, 87

Table 1. Summary of the Observational Results

R.A. (1950.0) Dec.	m_b	$b-r$	z	σ^a	M_b	EW^b	L_{OII}	R_{OII}
0 55 28.46 -27 35 50.5	21.83	1.07	0.28236	60 ± 08	-19.29	66	41.1	$1.36 \pm .10$
0 55 34.02 -27 35 09.5	21.32	1.16	0.34455	58 ± 05	-20.36	65	41.5	$1.26 \pm .06$
0 55 44.01 -27 40 42.4	21.52	1.07	0.21367	33 ± 23	-18.84	12	40.3	$0.62 \pm .15^*$
0 55 54.30 -27 41 59.0	21.60	0.96	0.21472	62 ± 11	-18.77	29	40.6	$1.32 \pm .12$
0 55 15.69 -27 49 56.6	21.69	0.92	0.20723	41 ± 16	-18.58	22	40.4	$1.55 \pm .17$
0 55 41.91 -27 53 38.2	21.41	0.35	0.34462	11 ± 14	-20.27	15	40.8	$0.94 \pm .15^*$
0 55 30.23 -27 57 48.4	21.36	0.92	0.23491	46 ± 08	-19.25	38	40.9	$1.48 \pm .10$
0 55 27.81 -28 00 48.6	21.40	0.71	0.18024	58 ± 19	-18.51	14	40.2	$1.53 \pm .22$
0 55 20.22 -28 00 29.2	21.75	0.34	0.15934	18 ± 18	-17.84	8	39.7	$1.26 \pm .34$
0 54 46.57 -28 00 56.6	21.25	0.52	0.26532	34 ± 12	-19.69	20	40.7	$1.57 \pm .16$
0 54 27.40 -28 02 31.9	21.69	0.77	0.16399	28 ± 21	-17.97	19	40.1	$1.10 \pm .16$
0 54 12.55 -28 07 32.3	21.39	0.83	0.21332	53 ± 09	-18.96	26	40.6	$1.40 \pm .11$
0 53 53.12 -28 04 53.7	21.94	0.80	0.32507	75 ± 24	-19.57	38	40.9	$1.51 \pm .21$
0 53 48.90 -27 55 59.3	21.38	1.08	0.23578	78 ± 15	-19.24	33	40.8	$1.34 \pm .12$
0 54 09.32 -27 54 49.2	21.79	0.81	0.21405	32 ± 19	-18.57	24	40.4	$1.66 \pm .22$
0 54 44.74 -27 52 34.8	21.47	1.01	0.27436	27 ± 18	-19.57	20	40.7	$1.45 \pm .16$
0 54 06.74 -27 51 14.0	21.87	1.05	0.21372	36 ± 11	-18.49	39	40.6	$1.55 \pm .15$
0 54 04.35 -27 48 44.0	21.65	1.16	0.24532	67 ± 27	-19.08	15	40.4	$0.50 \pm .38^*$
0 53 48.42 -27 44 59.4	21.32	1.09	0.23972	45 ± 58	-19.35	12	40.4	$0.79 \pm .21^*$
0 54 19.62 -27 48 08.4	21.35	1.18	0.21635	52 ± 05	-19.04	61	41.0	$1.26 \pm .07$
0 54 05.09 -27 45 08.8	21.39	0.94	0.28742	62 ± 18	-19.78	19	40.7	$1.34 \pm .20$
0 54 30.99 -27 49 18.0	21.73	1.04	0.33404	86 ± 17	-19.86	30	40.9	$0.58 \pm .14^*$
0 53 59.66 -27 37 45.1	21.42	1.17	0.23260	51 ± 15	-19.16	24	40.6	$1.08 \pm .13$
0 54 33.00 -27 45 05.7	21.68	0.92	0.29622	31 ± 10	-19.57	34	40.9	$1.05 \pm .12$

[a] The error listed is the geometric mean of the upper and lower error bar.

[b] The EW has been estimated from the observed [OII]line flux, the instrument efficiency and the b_j magnitude of the galaxy.

[c] The five galaxies where the line ratio is significantly (2σ) below 1.32 have been labelled with an asterisk. Their line ratios

indicate gas densities in excess of $100\mathrm{cm}^{-3}$, and may arise from an AGN, rather than HI regions in the galaxies' disks.

Table 2. Local Galaxies for Establishing $p(\sigma|v_c)$

Name	v[km/s]	M_B	$B-R$	v_{circ}	R_0[kpc]	i [°]	γ
ESO 215-G39	4335	-19.8	0.8	153	1.88	47	2.2
ESO 323-G73	5016	-19.9	1.0	157	1.83	48	2.3
ESO 437-G43	3801	-17.7	0.8	104	3.50	53	3.7